Predicting seismicity and ground motion along the Hayward fault using 3D distinct-element models

Luther M. Strayer, Ph.D., Dept. of Geol. Sci., Cal State Univ, Hayward, Hayward, CA, USA, luther.strayer@csueastbay.edu

INTRODUCTION AND OBJECTIVES

This work is based on the idea that fault-surface topography is the main influence on determining the location of single and repeater earthquakes, and that an understanding of fault surface geometry is therefore crucial to predicting the location and future seismicity.

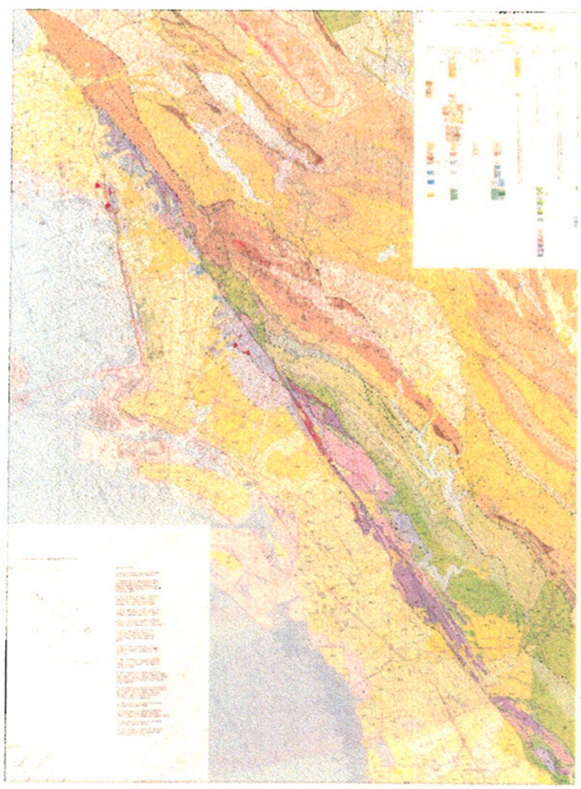


Figure 1. Graymer's (2000) geologic map of the Oakland Metropolitan area, showing the surface-trace of the Hayward fault. This is the portion of the HF being considered in this work

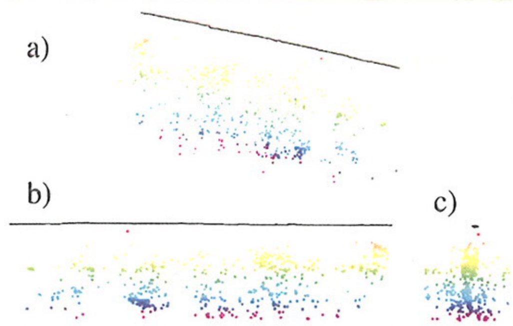


Figure 2. Double-difference relocated hypocenters (Waldhauser & Ellsworth 2000) colored according to depth. a) view toward north. b) view toward east. c) view toward northwest.

The intent of this research is to incorporate fault geometry models (FGM) into 3D, fully-dynamic, numerical bonded-particle models (BPM) of the Hayward fault, and to generally predict the pattern, distribution and magnitude of earthquakes as the result of slip upon the modeled Hayward fault.

The location and distribution of historical hypocenters below the mapped surface trace of the Hayward fault (HF) (Fig. 1) is the best tool we have to define the shape of the actual fault surface. Because high-quality, accurate earthquake locations are crucial to this enterprise, we have chosen to use double-difference relocated hypocenters (Waldhauser & Ellsworth 2000) (Fig. 2) to define the fault plane and to construct three-dimensional fault-surface geometry models of the Hayward fault (Figs, 3, 4 & 5).

The Hayward fault-surface models are then incorporated into forward, dynamic, distinct-element (bonded particle) (Fig. 6) numerical models of the Hayward fault in the region between Richmond and Hayward, California (Figs. 1, 7 & 8). We are using the finite-difference, distinct-element modeling (DEM) software *PFC3D* (Particle Flow Code in 3D), to create a bonded-particle model of rock for this region. This sort of BPM formulation has been shown to well reproduce elastic and subsequent brittle-plastic mechanical behavior of rock, and most exciting - to simulate brittle failure in the form of 'micro-cracks' (failed particle bonds) that, upon progressive loading, link up to produce true faults within the model (Potyondy & Cundall 2004).

The particle model extends down to a depth of 12 km (Fig. 3) and is effectively divided in half by a discrete boundary (the fault) that has a geometry that matches that of our model of the Hayward fault (Fig. 4). The BPM in fully dynamic mode can simulate seismicity resulting from slip upon the modeled fault as well as new fracture of intact rock adjacent to the fault. Any

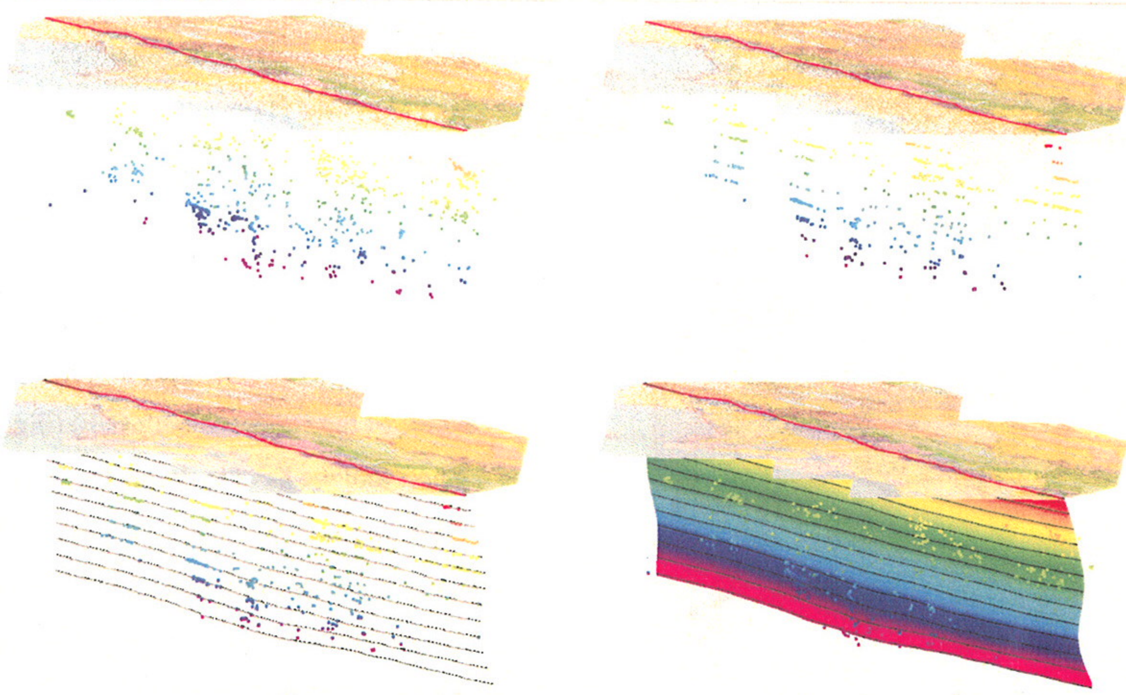


Figure 3. The Hayward fault-surface geometry model (FGM) is constructed from a series of best-fit lines at kilometer intervals, down to a depth of 12 km, and then fitting a surface to those lines.

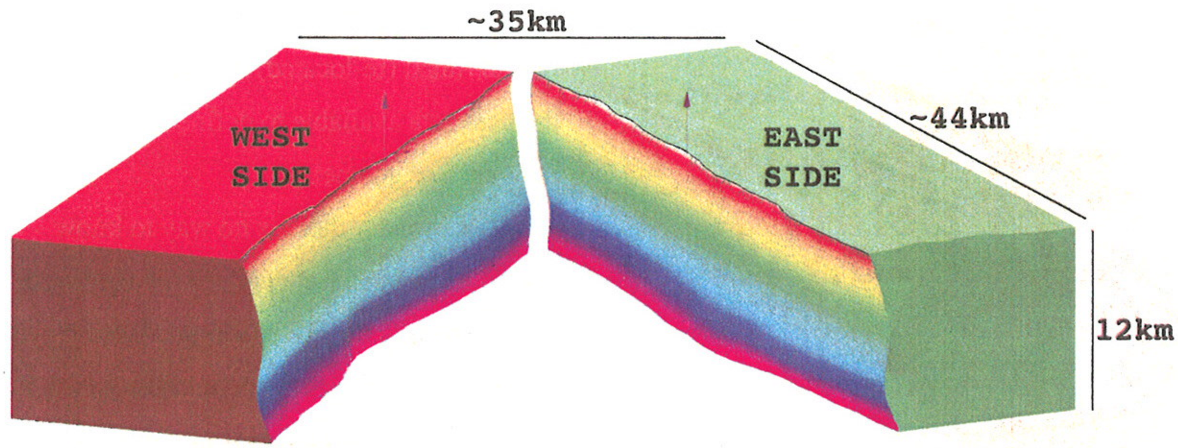


Figure 4. Dimensions of the bonded-particle model (BPM) showing the fault-surface geometry model (FGM).

particle within the BPM can serve as a seismograph (Fig. 8) – recording any motion that results from nearby or distant bond-breakage or particle slip on or off the fault (Fig. 9 & 10). We can make maps of ground motion anywhere in the model in response to our model earthquakes.

The goal is to produce mechanical models that simulate generally both in spatial pattern and magnitude, the historical seismicity on and near the HF, and to characterize ground surface motion in the East Bay . Other goals and currently on-going work include: 1) investigating the kinematics of individual fault slip events - identifying the size and shape of the rupture and the geometry of the rockmass that is active (accelerating) adjacent to the propagating rupture, and; 2) investigating the importance of different lithologies on either side of the fault. It may well be that re-creating the distribution of historical earthquakes in the BPM model will require patches of the fault to have modified mechanical properties as indicated by 3D velocity models of the Bay Area (c.f. Jachens et al. 2001), thus indicating that fault-surface lithology *and* topography are fundamentally linked in their

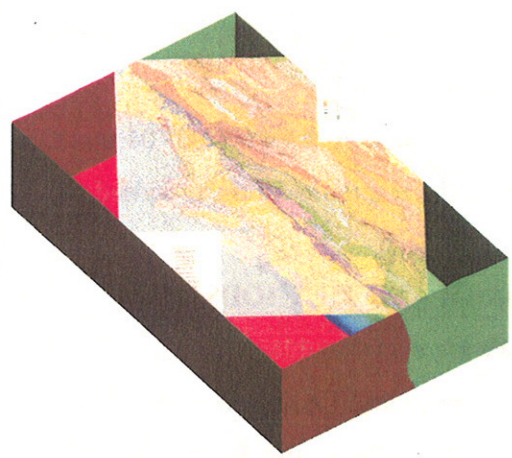


Figure 5. The domain of the fault-surface geometry model (map) and the extent of the boundaries of the bonded particle model. The left (red) side is moved according to geodesy and the right (green) side is fixed.

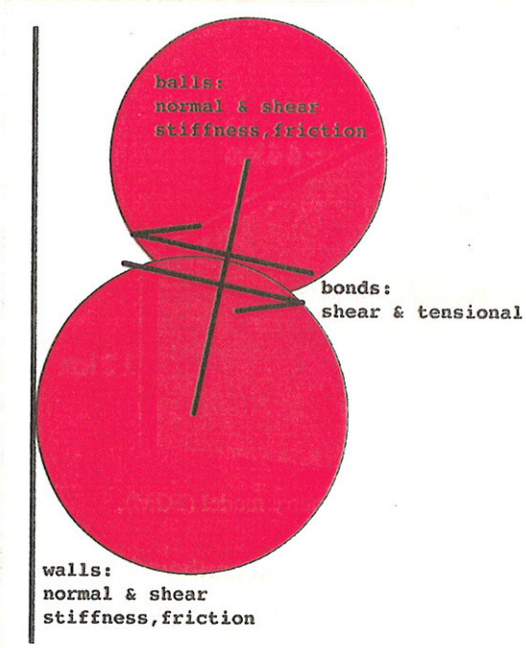


Figure 6. The mechanical behavior of the BPM is defined by particle stiffness, friction and bonding micro-properties, and initial stress-state. Micro-properties and packing arrangement determine the emergent rockmass macro-properties.

influence on the distribution of earthquakes upon a fault. There are numerous other avenues of research that could result from these initial models.

The research goal for FY'03-'04 was to demonstrate the feasibility of the proposed modeling approach.

APPROACH AND METHODS

We are using double-difference relocated hypocenters (Waldhauser & Ellsworth 2000) (Fig. 2) and the main trace of the HF (Lienkeamper 1992) (Fig 1) to define a curvi-planar fault surface. We believe that in the absence of high-resolution 3D reflection and/or refraction data that might define the true geometry of the HF, that the locations of individual (re-located) hypocenters are the best data available to define the actual fault surface geometry

Currently there is no way to know the 'true' geometry at depth of the Hayward fault. Treating the HF as a single curvi-planar surface when it may be actually a 1-3 km wide zone of anastamosing faults as seen on the surface (Graymer 2000) (Fig 1), is a necessary simplification of the geometry problem. We use the mining visualization and modeling software *Vulcan* for fault model construction and later to aid in the construction of the bonded-particle model. Using the re-located hypocenters, we constructed a best-fit plane (Fig. 3) through the 'curtain' of data that fall beneath the

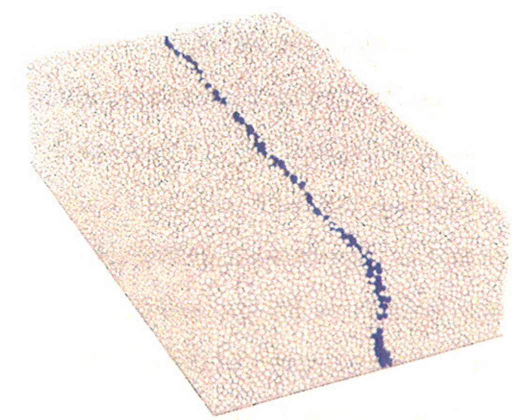


Figure 7. The BPM showing the fault surface, here shown as a finite-width zone of particles with geometry defined by the FGM shown in Figs. 3,4 & 5. Highest resolution model has approx. 100,000 particles.

surface trace of the HF. This process can be strongly hand-guided (hand-fitting lines through either vertical or horizontal sections of data and then fitting a surface to them) or nearly completely black-box (surface fitting algorithms applied to the data curtain).

The hand-guided nature of the process, and variation of the 'black-box' surface fitting parameters ensures that this process does not produce unique results. Indeed, subsequent attempts by the same or different workers using the same data yields somewhat differing results, but robust fault-surface

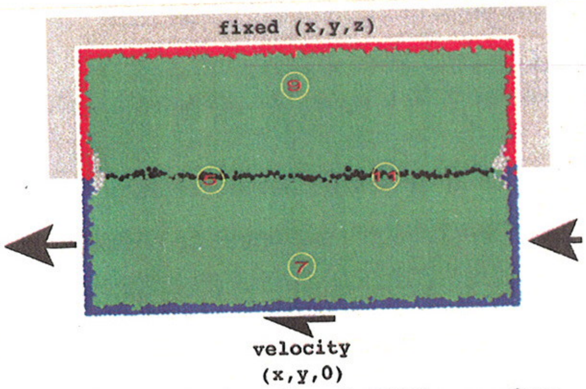


Figure 8. Boundary conditions for BPM as seen from above. Also show are the locations of 4 (#'s 5, 7, 9 & 11) out of 16 'seismograph' particles on the model ground surface.

features/asperities are present regardless of the details of fault-surface construction.

The curvi-planar geometry of the FGM is input into a 3D rectangular array of bonded particles (45 km by 33 km by 12 km deep) as either: 1) a *discrete boundary* that cleanly separates the model into 2 blocks on either side of the fault, or; 2) a *finite-width zone* of un-bonded or weakly bonded particles – representing a fault *zone* that conforms to the shape of our modeled fault plane, and that separates the blocks on either side of the fault (Fig. 7).

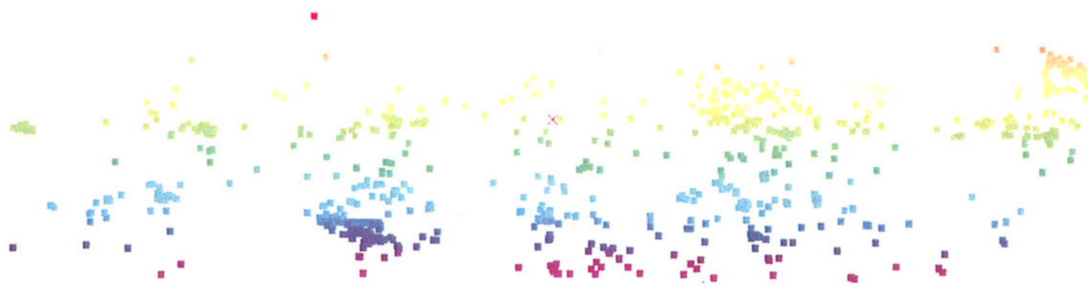
The fault divides the particle array defining a fixed (in x, y & z) east-side, and a west-side that has velocity boundary conditions defined by geodesy To monitor ground motion, any particle in the model can serve as a seismograph, recording velocities, allowing us to create strong-motion maps of the model ground surface.

ACCOMPLISHMENTS & RESULTS

To date we have developed:

1) 3D geologic modeling tools and a methodology to develop detailed fault-geometry models (FGM) from high-quality hypocenter locations and detailed surface mapping, and also methods to incorporate ASCII x, y, z fault surface (and volumetric, i.e. rockmass) data from the model-building/visualization software into a bonded-particle model.

We have found the *Vulcan* software to be extremely capable in the area of model building, i.e. line and surface fitting, but it also, due to it's mining pedigree has built-in logic for dealing with spatial variations of rock material properties within volumes and a)



b)

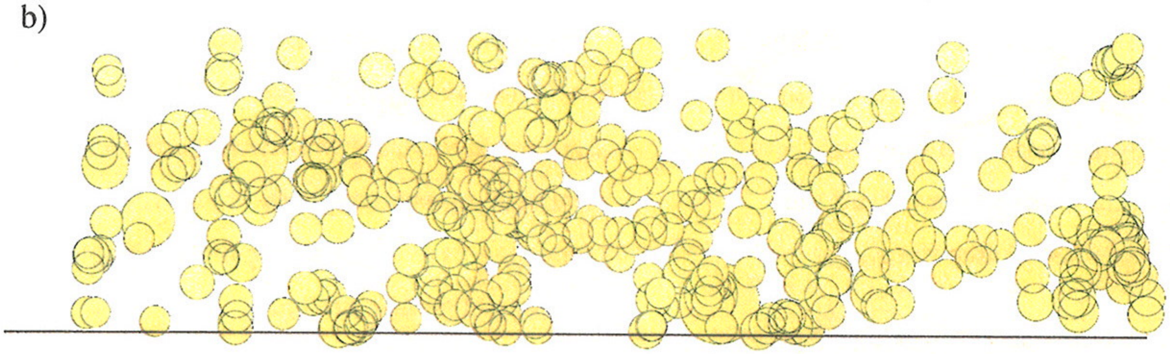


Figure 9. Comparison between a) historical double-difference relocated seismicity of (Waldhauser & Ellsworth 2000), and b) model hypocenters from the BPM. There are some obvious similarities in regions with few or no events. View is toward the NE.

strong database /data manipulation capabilities. Its modest price (~$3400 academic price FY-04) and similar or superior abilities in comparison to *Gocad* or *EarthVision* makes it a good choice for this type of work.

2) A geometric fault-surface model of the Hayward fault in the Oakland metropolitan area (Graymer's (2000) map) extending down to a depth of 12 km (Fig. 3).

The current model was made by 'eye-balling' a best-fit curve through the 'curtain' of hypocenters at kilometer intervals, down to a depth of 12 km. A fault surface was then fit to these 12 fault traces that represent the fault's structure contours. The surface is then smoothed to the degree that the resulting surface has a roughness (judged by eye) that is similar to but not rougher than the surface trace of the fault (Lienkeamper 1992). The current FGM compares favorable with an independently but similarly derived Hayward fault surface-geometry model created by Robert Simpson of the USGS, Menlo Park (Simpson personal comm.). We used the same hypocenters and surface-trace data, and as expected, the models are similar where data is the most abundant and differ most where data are sparse, although his model has less topography.

3) Two differently discretized (~0.5 km & ~1km dia.) distinct-element, bonded-particle mechanical models of the Hayward fault from Richmond to Hayward. We have developed tools that allow us to: import a variety of fault geometries; assign differing material properties to specific regions of the fault surface or any 3D volume anywhere in the model; and easily vary boundary conditions to account for different geodesy.

4) We have developed, modified and implemented numerical subroutines that identify the location and quantify the magnitude of seismic events (both bond-breakage and slip).

Early results from this work are promising. The fault geometry model is a good framework within which we can modify the HF, and in the future add other faults, both strike- and dip-slip, which are shown on Graymer's (2000) map. The fault geometry model is easily output in ASCII format at a variety of mesh resolutions for sharing with other workers.

Having worked out a significant number of complicated issues, both mundane (developing data interfaces between the FGM and the BPM) and more exotic (details of the seismicity-identification and quantification subroutines), the mechanical model now operates stably. Results from early model runs show good qualitative similarity between the both the spatial distribution and range of magnitudes for model earthquakes when compared with the historical seismicity. Model moment magnitudes range from ~2 to ~6 with the expected frequency magnitude relationship making the 6's very rare. Currently, the model will collect ground motion resulting from rupture or slip events that occur anywhere in the model – on the fault or off.

REFERENCES

Graymer, R.W., Geologic Map and Map Database of the Oakland Metropolitan Area, Alameda, Contra Costa, and San Francisco Counties, California, *USGS Miscellaneous Field Studies MF 2342*, Online Version 1.0, 2000.

Jachens, R.C., Wentworth, C.M., McLaughlin, R.J., Fitzgibbon, T.T., Phelps, G.A., Langenheim, V.E., Graymer, R.W., and Stanley, R.G., 2001, 3-dimensional geologic map of the Santa Clara ("Silicon") Valley, California, : Geological Society of America 2001 Abstracts with Programs v. 33, p. A-39.

Lienkaemper, J.J., 1992, Map of recently active traces of the Hayward Fault, Alameda and Contra Costa counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF– 2196, 13 p. (1 sheet).

Potyondy, D.O. and P.A. Cundall, 2004, A bonded-particle model for rock. *Int. Jour. Rock Mechs & Mining Sci.* 41. 1329–1364

Waldhauser, F., and Ellsworth, W.L., Fault structure and mechanics of the Hayward Fault, California, from double-difference earthquake locations, J. Geophys. Res., 107 (3), 2002

PUBLICATIONS (FYO4)

STRAYER, Luther M., 2004. 3D geometric models of the Hayward fault for use in distinct-element models of Bay Area deformation and seismicity. GSA Annual Meeting, Program w/ Abstracts, Paper No. 51-4.

STRAYER, Luther M., 2004. 3D Geometric and distinct-element models of deformation and seismicity on the Hayward fault: initial model and early results. *Eos Trans.* AGU 85(47) Fall Meeting Suppl., p. F1367.